14

(12) UK Patent Application (19) GB (11) 2 307 059 (13) A

(43) Date of A Publication 14.05.1997

(21) Application No 9622270.8

(22) Date of Filing 25.10.1996

(30) Priority Data
(31) 07281941 (32) 30.10.1995 (33) JP

(71) Applicant(s)
Fuji Electric Co Ltd

(Incorporated in Japan)

1-1 Tanabeshinden, Kawasaki-ku, Kawasaki-shi, Kanagawa 210, Japan

(72) Inventor(s)
Takeshi Kobayashi
Tetsuya Saitoh

(74) Agent and/or Address for Service
G F Redfern & Co
Redfern House, 149/151 Tarring Road, WORTHING, West Sussex, BN11 4HE, United Kingdom

(51) INT CL^6
G02B 6/26

(52) UK CL (Edition O)
G2J JGEC

(56) Documents Cited
None

(58) Field of Search
UK CL (Edition O) G2J JGEC , H4B BK20S1
INT CL^6 G02B , H04B 10/20
Online databases : WPI

(54) **Optical star coupler with reflector portion**

(57) An optical star coupler is has bundling means 2 comprising a bundle of optical fibres 11-1E connected to mixing means 3 comprising a waveguide 31 and a diffuser-reflector means 4 comprising a terminal mirror 41 having a reflection plane 42 and light diffusion layer 43,44,45. The bundling means 2 is arranged so as to form a flat plane 32 and has a light reflector 23 formed on part of the plane. The diffuser-reflector 4 is arranged to connect to the other end of the mixing means 3. The diffuser-reflector 4 allows the optical signal radiated from one of the optical fibres to be distributed uniformly across the waveguide 31 so that the optical signal is efficiently distributed to the other optical fibres. The optical star coupler may also have a reflector portion (4A, figure 7A and 4C, figure 8A) in place of the diffuser-reflector portion.

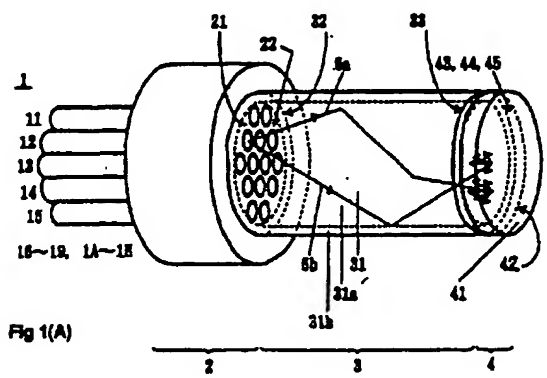


Fig 1(A)

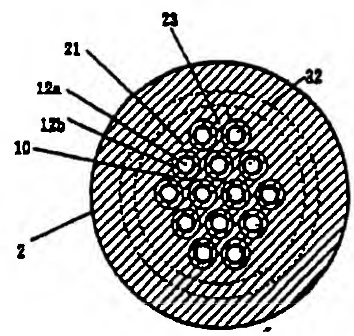


Fig 1(B)

GB 2 307 059 A

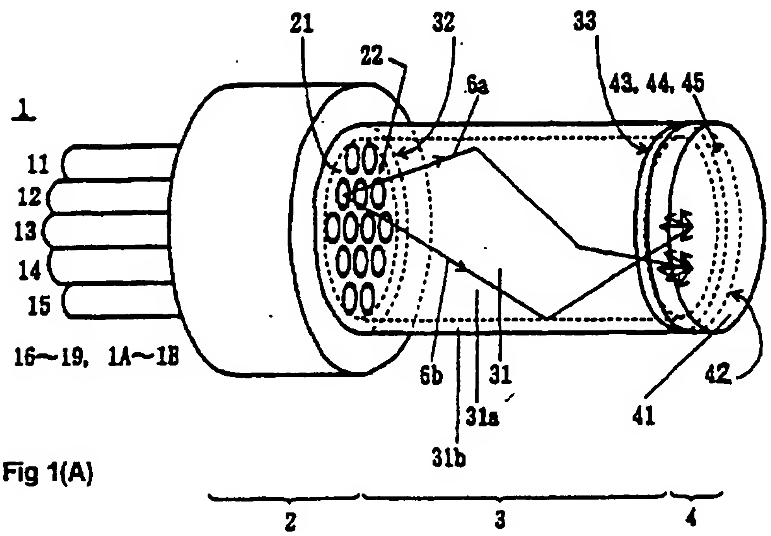

1
11
12
13
14
15
16~19, 1A~1B
21
22
32
6a
33
43, 44, 45
6b
31
31a
31b
41
42
2
3
4

Fig 1(A)

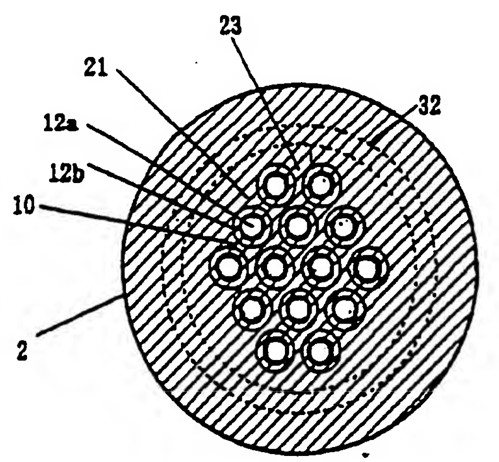
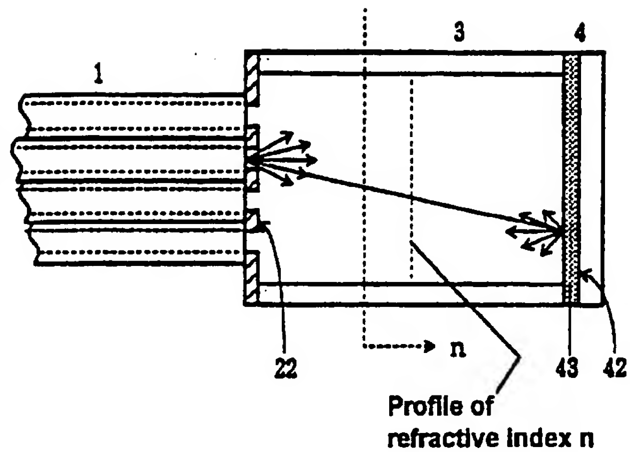
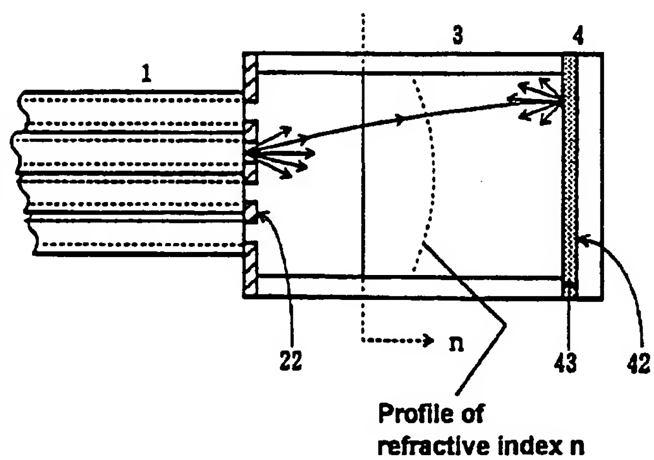

23
21
32
12a
12b
10
2

Fig 1(B)



3
4
1
11
12
13
14
22
n
43
42
Profile of refractive index n

Fig 2(A)



3
4
1
11
12
13
14
22
n
43
42
Profile of refractive index n

Fig 2(B)

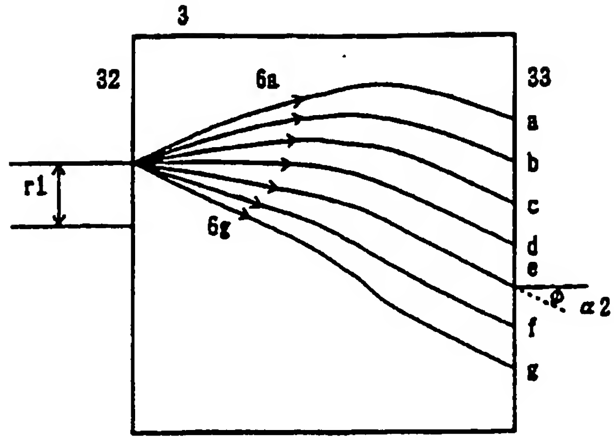


Fig 3(A)

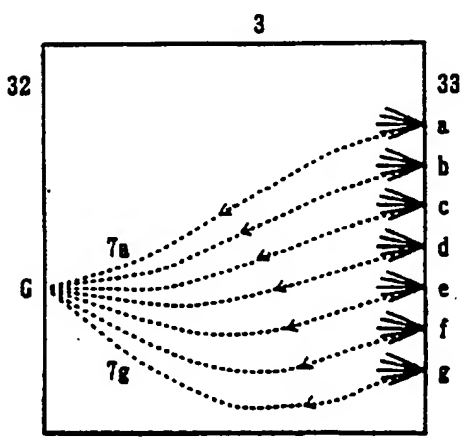


Fig 3(B)

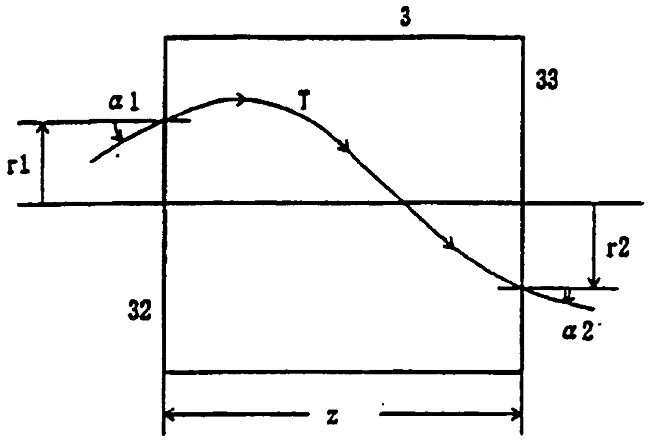


Fig 4

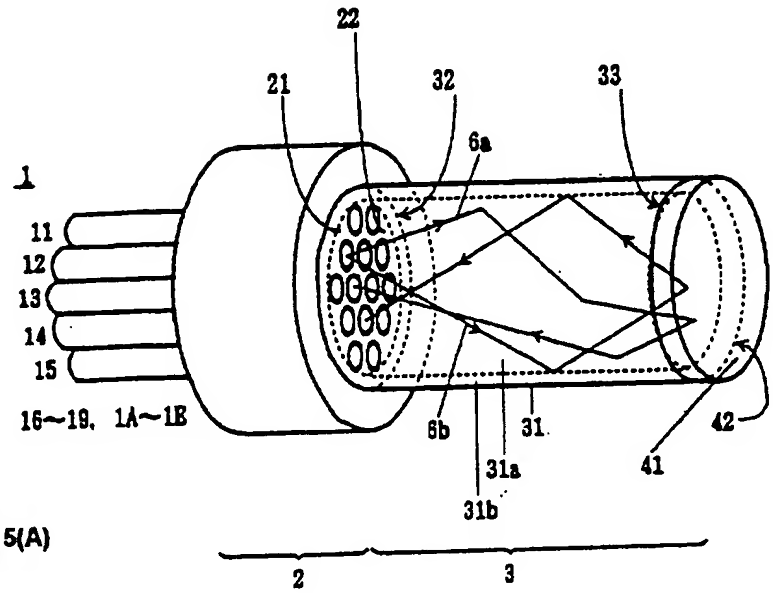

22
21
32
33
6a
1
11
12
13
14
15
16~19, 1A~1E
6b
31
42
41
31a
31b
2
3

Fig 5(A)

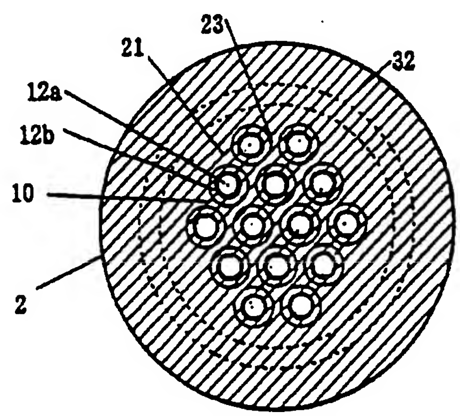

23
21
32
12a
12b
10
2

Fig 5(B)

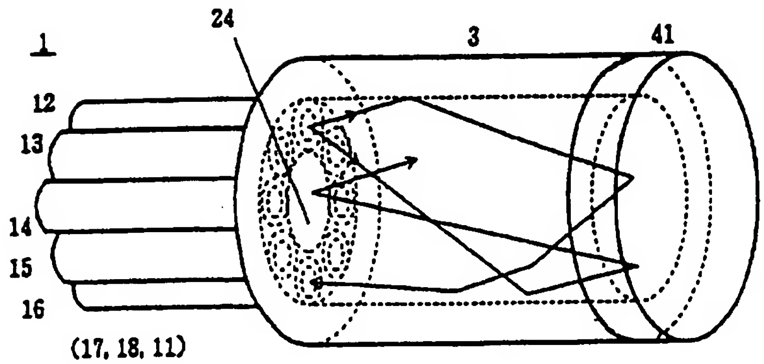


Fig 6(A)

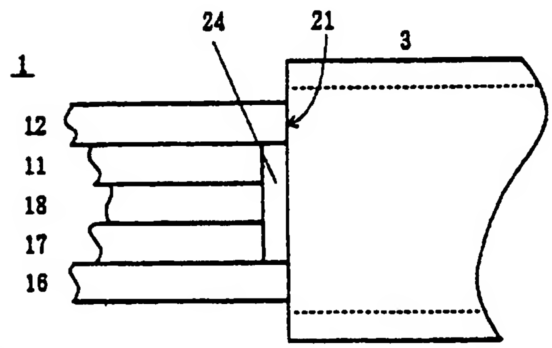


Fig 6(B)

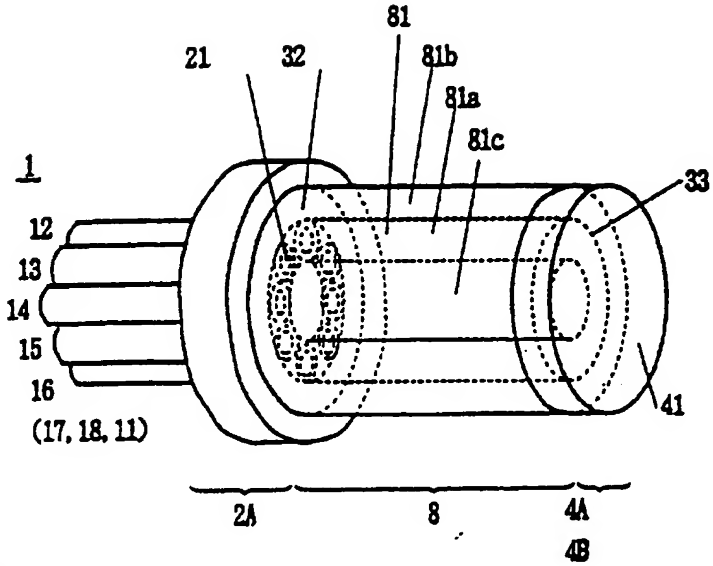

1
12
13
14
15
16
(17, 18, 11)
21
32
81
81b
81a
81c
33
41
2A
8
4A
4B

Fig 7(A)

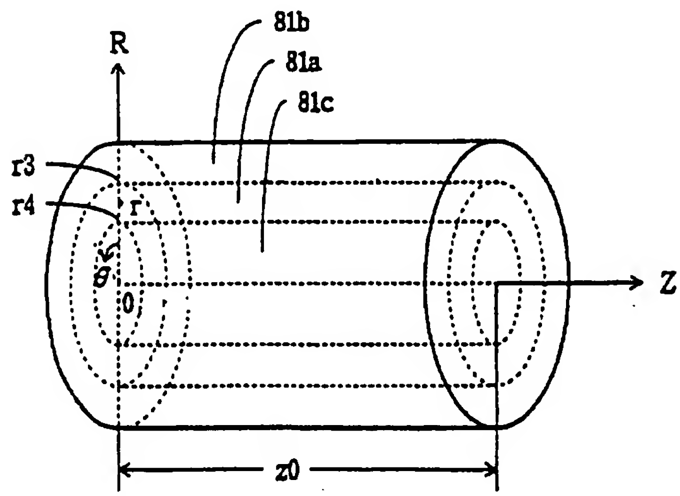

R
81b
81a
81c
r3
r4
r
θ
0
Z
z0

Fig 7(B)

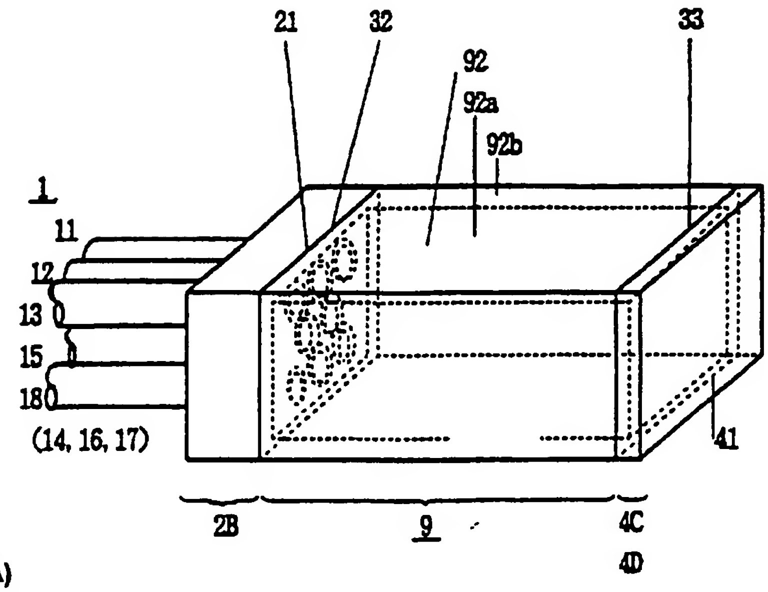

21
32
33
92
92a
92b
1
11
12
13
15
18
(14, 16, 17)
41
2B
9
4C
4D

Fig 8(A)

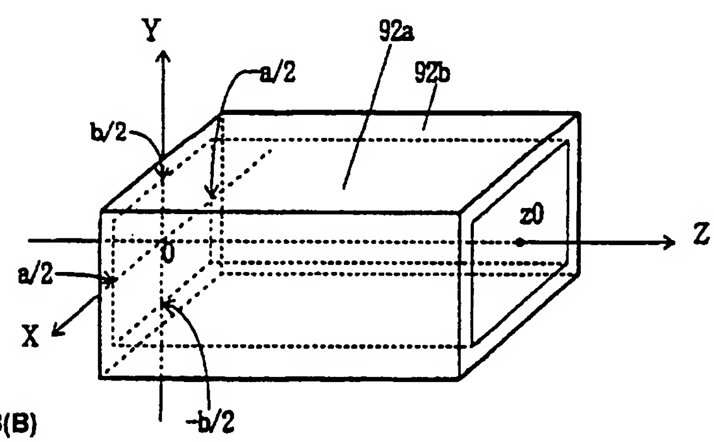

Y
92a
a/2
92b
b/2
z0
Z
0
a/2
X
-b/2

Fig 8(B)

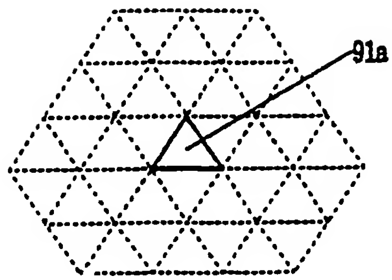


Fig 9(A)

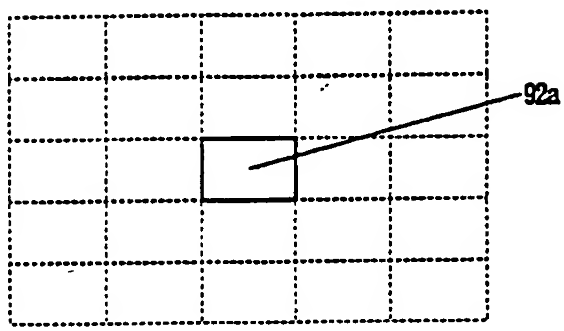


Fig 9(B)

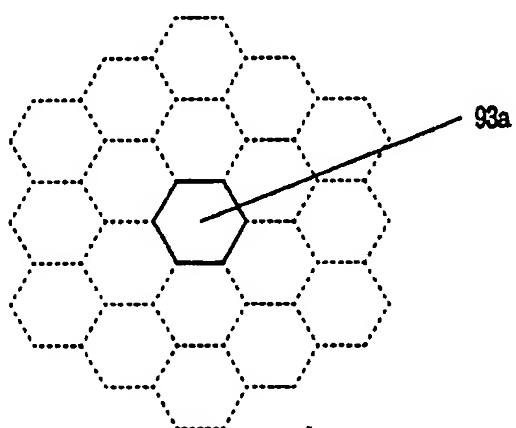


Fig 9(C)

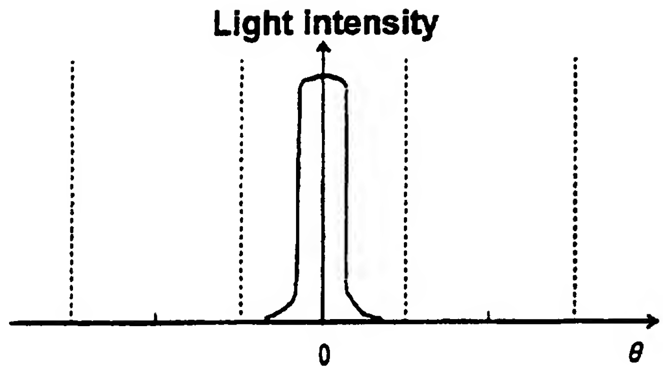


Fig 10(A)

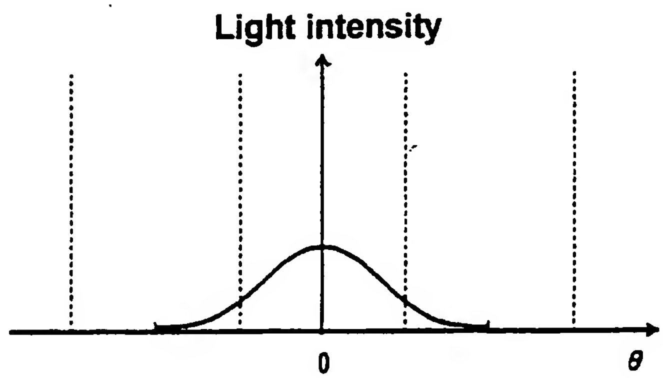


Fig 10(B)

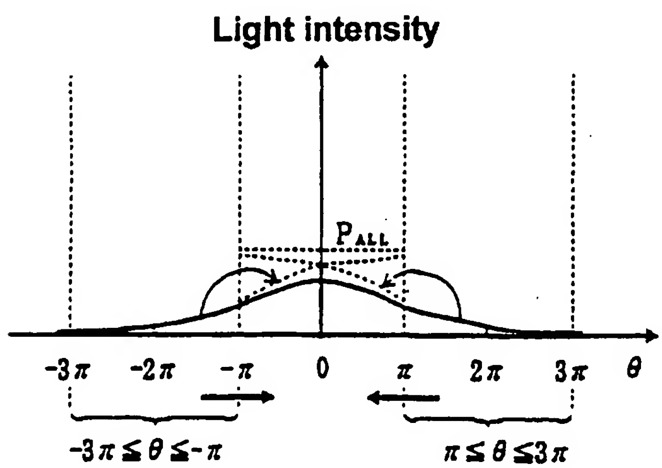


Fig 10(C)

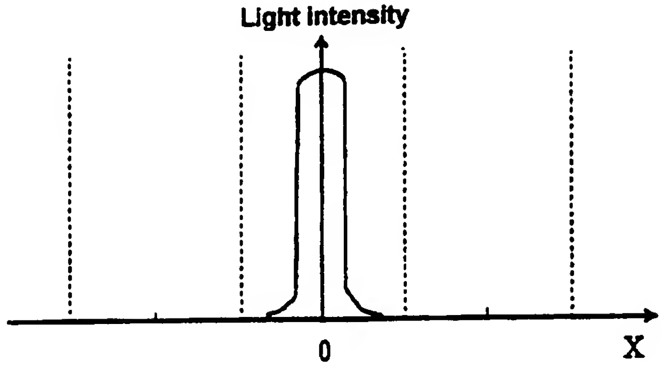


Fig 11(A)

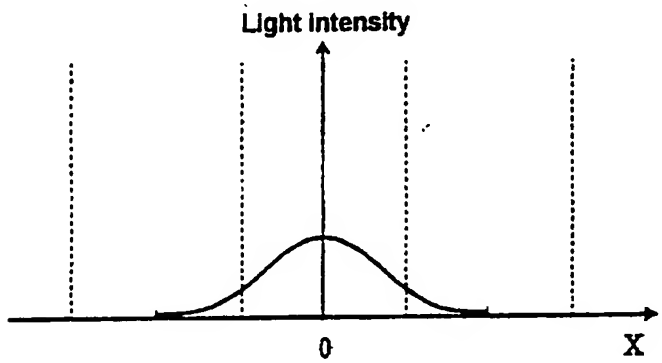


Fig 11(B)

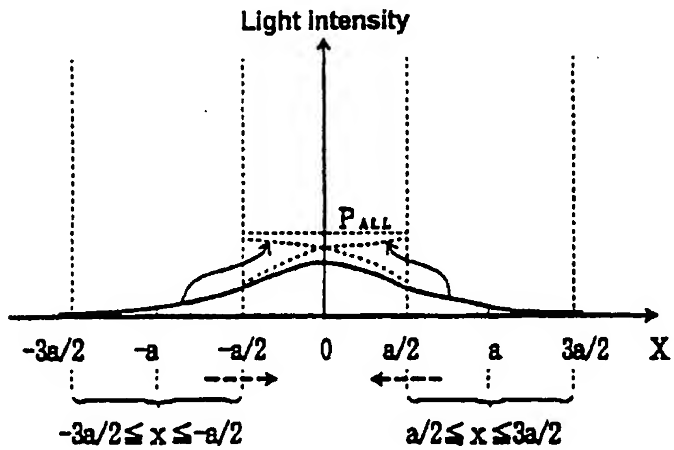


Fig 11(C)

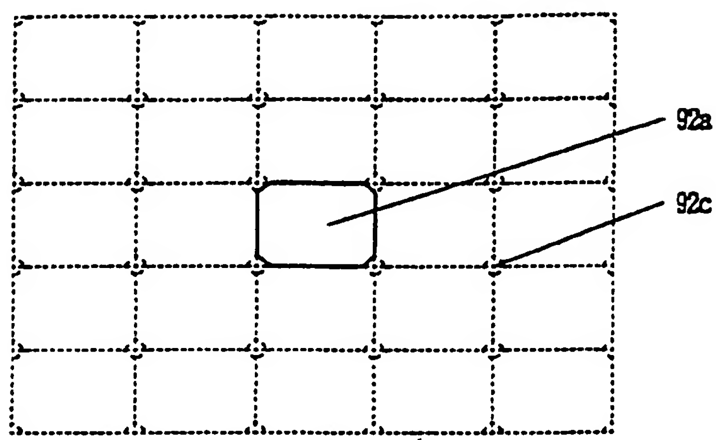


Fig 12

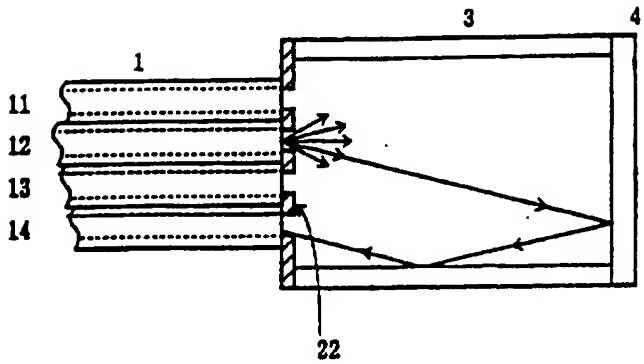


Fig 13(A)

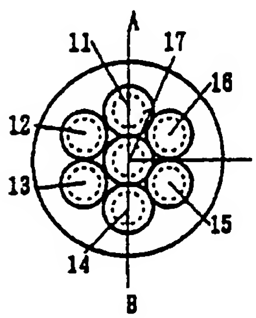


Fig 13(B)

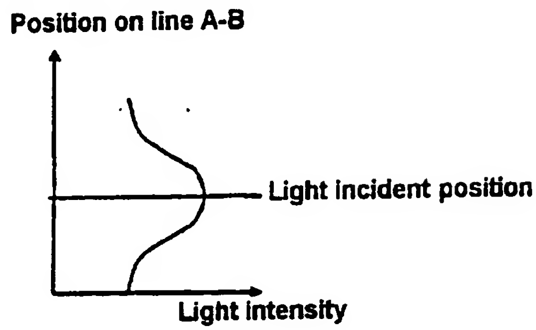


Fig 13(C)

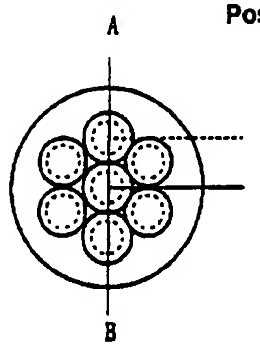


Fig 13(D)

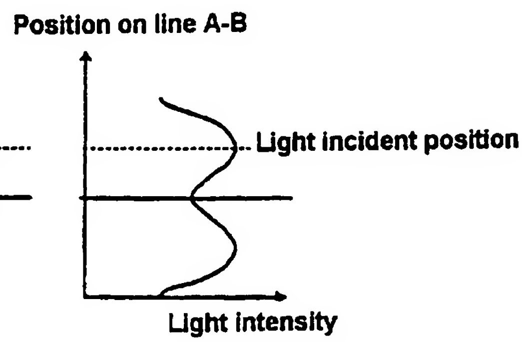


Fig 13(E)

OPTICAL STAR COUPLER

The present invention relates to an optical star coupler which couples a number of optical fibres, one of which carries an optical signal which is to be coupled to the other optical fibres with a low transmission loss. The coupler can also gather optical signals to be placed onto one optical fibre with a low transmission loss.

It is often necessary when constructing an optical transmission network to use an optical star coupler that distributes an optical signal to a plurality of optical fibres and gathers a plurality of optical signals to be placed on one optical fibre. These types of optical star couplers are disclosed in Unexamined Japanese Laid Open Patent Application No. S59-126510 and US Patent No. 4,365,864. Figures 5(A) and 5(B) show a conventional optical star coupler whose parts relevant to the present invention are indicated and arranged for the sake of explanation.

Referring now to Figures 5(A) and 5(B), a plurality of optical fibres 11 to 15 and 16 to 1E (not shown) (hereinafter, the optical fibres are designated by 11 to 1E) is fixed with the first ends thereof bundled to the conventional optical star coupler. The bundled first ends of the optical fibres 11 to 1E are arranged so as to form a flat end face 21. A light reflector 22 is disposed on a part of the end face 21. The bundled first ends of the optical fibres 11 to 1E, the end face 21 and the light reflector 22 constitute a bundling means 2. A mixing means 3 includes a waveguide 31 whose first end face 32 contacts the end face 21 of the bundling means 2. The first end face 32 of the waveguide 31 is wide enough to cover at least the cores 11a to 1Ea of the optical fibres 11 to 1E. A terminal mirror 41 is disposed on the second end face 33 of the mixing means 3. The terminal mirror 41 has a reflection plane 42.

In the structure shown in Figures 5(A) and 5(B), the end face 21 of the bundling means 2 is bonded to the first end face 32 of the mixing means 3, which comprises a transparent cylindrical optical glass rod. The terminal mirror 41 is bonded to the second end face 33, which is on the opposite end of the mixing means 3 facing toward the first end 32. The waveguide 31 of the mixing means 3 consists of a cylindrical core 31a and

a cladding 31b formed on the side face of the cylindrical core 31a. The refractive index of the cladding 31b is set lower than that of the core 31a.

In the conventional optical star coupler of Figures 5(A) and 5(B), optical signals 6a, 6b radiate, for example, from the optical fibre 12 and diverge across the waveguide 31. A portion of the diverging optical signals propagates through the mixing means 3 while being totally reflected on the peripheral surface of the mixing means 3 and reaches the terminal mirror 41. Then, the optical signals 6a, 6b, reflected by the terminal mirror 41, propagate back through the waveguide 31 to the optical fibres 11 to 1E. The optical signals 6a, 6b which have reached the cores 11a to 1Ea of the optical fibres 11 to 1E are output through the optical fibres.

In the illustrated conventional optical star coupler of Figures 5(A) and 5(B), the terminal mirror 41 having an optical reflecting means (reflection plane 42) is formed on the second end face 33 of the mixing means 3. Another optical reflecting means (reflection plane 23) is formed in the spaces 10 extending between the cores 11a to 1Ea of the optical fibres 11 to 1E. The space 10 covers the end face of the cladding 11b to 1Eb of the optical fibres 11 to 1E. For example, an optical signal radiated from the optical fibre 12 is reflected at the reflection plane 42 and diverges almost uniformly over the entire end face 21 when the mixing means 3 is sufficiently long. The incident optical signal to the cores 11a to 1Ea is output through the optical fibres 11 to 1E in the form as it has reached the cores. The signal incident on the spaces 10, inclusive of the claddings 11b to 1Eb, is reflected repeatedly by the reflection planes 23 and 42 until it is finally outputted down a fibre. As a result, an optical signal radiated from the optical fibre 12 is distributed to the other optical fibres.

Another conventional optical star coupler disclosed in US Patent No. 4,365,864, which will also be described referring to Figures 5(A) and 5(B), has a total reflection mirror that corresponds to the terminal mirror 41. An apertured mirror having apertures thereon corresponds to the light reflector 22 formed on a part of the end face 21. The optical

signals 6a, 6b are radiated from the cores 11a to 1Ea of the optical fibres 11 to 1E to the mixing means 3 through the apertures of the apertured mirror. The optical signals 6a, 6b radiating, for example, from the optical fibre 12 to the mixing means 3 are reflected by the reflection plane 42 and diverge almost uniformly over the end face 21. The optical signal incident on the cores 11a to 1Ea is output through the optical fibres 11 to 1E. The optical signal incident on the space 10, inclusive of the claddings 11b to 1Eb, is reflected repeatedly by the reflection planes 23 and 42 and finally output. As a result, an optical signal radiated from the optical fibre 12 is distributed to the other optical fibres. The apertured mirror is formed on the end face 21 of the bundling means 2 or on the first end face 32 of the mixing means 3.

The dimensions of the mixing means 3 are properly chosen so that the optical signals 6a, 6b, radiating to the waveguide 31 and reflected at the reflection plane 42, may diverge uniformly over the end face 21. However, it has been found experimentally that when light is incident on the central portion of the waveguide 31, the intensity tends to lower in the peripheral portion of the waveguide 31, and that when light is incident on the peripheral portion of the waveguide 31 the intensity tends to lower in the central portion of the waveguide 31. Figures 13(A) to 13(E) show an example of the experimental results.

Figure 13(A) is a schematic longitudinal cross-section of the foregoing optical star coupler having optical fibres 11 to 17. Figures 13(B) and 13(D) are schematic radial cross-sections showing the arrangement of the optical fibres 11 to 17 of the optical star coupler of Figure 13(A). Figure 13(C) is a light intensity distribution on the line A-B of Figure 13(B) when a light signal is radiated from the optical fibre 17 coupled to the central part of the waveguide 31. Figure 13(E) is a light intensity distribution on the line A-B of Figure 13(D) when a light signal is radiated from the optical fibre 11 coupled to the peripheral part of the waveguide 31. When a light signal is radiated from the optical fibre 17, the light intensity tends to be higher in the central part of the radial cross-section of the waveguide 31 and lower in the peripheral part thereof. When a light signal is radiated from the optical

fibre 17, the light intensity tends to be higher in an annular zone, facing directly to the optical fibres 11 to 16, of the radial cross-section of the waveguide 31 and lower in the central part thereof. In any occasion, the intensity of light radiated from the optical fibres 11 to 17 exhibits a certain distribution.

Figures 6(A) and 6(B) show another conventional optical star coupler proposed to solve the above described problem. In contrast to the optical star coupler of Figures 5(A) and 5(B), optical fibres are not bonded to the central part of the mixing means 3 where the light intensity tends to be lower, but a circular mirror 24 is arranged in the central part of the mixing means 3. In other words, a plurality of optical fibres 11 to 18, arranged and bundled into a cylindrical tube, is bonded to the first end face 32 of the mixing means 3. The circular mirror 24 is formed on the first end face 32 of the mixing means 3 and is situated within the tubular bundle of the optical fibres 11 to 18. A terminal mirror 41, having its reflection plane 42, is formed on the second end face 33 of the mixing means 3. An optical signal radiating, for example from the optical fibre 12, propagates through the mixing means 3 while diverging and is reflected by the terminal mirror 41 back to the optical fibres 11 to 18. The light which has reached the cores 11a to 18a of the optical fibres 11 to 18 is output through the optical fibres. The light which has reached the circular reflection mirror 24 is reflected again and propagates back and forth across the mixing means 3.

In the conventional optical star couplers described above, the intensity of the light, radiated from an optical fibre and propagating through the mixing means, distributes in rotational symmetry in most cases around the central axis of the mixing means 3 on the radial cross-section parallel to the end faces of the mixing means. The light intensity distribution is not uniform over the radial cross-section of the mixing means. Therefore, when an optical fibre bundle that simply bundles a plurality of optical fibres is used, the intensity of light distributed to the optical fibres is different from fibre to fibre.

To equalise the intensity of light distributed to each of the optical fibres, one possible arrangement is one that arranges the optical fibres in an annular zone spaced a certain distance from the central axis. However, the optical fibres and the mixing means should be specifically arranged with respect to one another within a narrow positional tolerance so that the light intensity may be substantially the same for the optical fibres. That is, the optical fibres and mixing means should be positioned quite accurately.

If a gap is left between the circular mirror and each optical fibre, the light that has reached the gap from the mixing means radiates outside the optical fibres to cause transmission loss. In the same way, any light that has happened to enter the cladding of the optical fibres through the gap has no chance to propagate through the optical fibres, and transmission loss will be caused. The loss is hazardous for efficient utilisation of the optical signals.

In view of the foregoing, it is an object of the invention to provide an optical star coupler that distributes the optical signal radiated from an optical fibre uniformly across the mixing means and couples the distributed optical signal efficiently to the other optical fibres.

According to a first aspect of the present invention, there is provided an optical star coupler that includes: a bundling portion including a plurality of optical fibres each having a core and a first end, the first ends being bundled together and the faces of the first ends of the fibres being arranged in a flat plane; a mixing portion including a waveguide, a first end face of which contacts the flat plane of the bundling portion and covers the cores of the optical fibres; and a diffuser-reflector portion coupled to the second end face of the waveguide.

In the configuration of the present invention, the incident optical signal light radiated from the bundling portion to the mixing portion is diffused and reflected at the diffuser-reflector portion coupled to the second end face of the waveguide. The optical signal light is diffused and reflected with a predetermined intensity distribution, and

the reflected optical signal light is distributed uniformly onto the first end face of the waveguide. Thus, the distribution ratios of the light radiated from an optical fibre and the incident light to the other optical fibres do not deviate so much from one another even when the optical fibres are displaced by different amounts from the axis of the mixing portion.

Advantageously, the waveguide is a graded-index optical waveguide, the refractive index of which is arranged to be higher around the central axis of the waveguide.

It is preferable to set the distance between the first and second end faces of the waveguide at a value that fixes the exit position of a ray on the second end face of the waveguide in response to the incident direction of the ray to the first end face of the waveguide

In this configuration, the optical signal light, radiated from any one of the optical fibres, propagates while being refracted, and reaches the light diffusion layer. The optical signal light enters the light diffusion layer at a position and in a propagation direction determined by the position of the optical fibre from which the optical signal light was radiated, and the incident direction of the optical signal light to the waveguide depends on the re-entrant direction of the signal light to the waveguide. Then, the optical signal light is diffused in the light diffusion layer, reflected by the terminal mirror, diffused again in the light diffusion layer, and radiated back into the waveguide. The optical signal light radiated into the graded-index optical waveguide propagates through the waveguide and reaches the first end face of the waveguide. The position, where the optical signal light reaches, distributes in various locations on the first end face of the waveguide. Thus, the optical signal light is distributed uniformly on the flat plane of the bundling portion. The uniformly distributed optical signal light then enters the optical fibres.

By setting the distance between the first and second end faces of the waveguide at a value that fixes the exit position of a ray on the second end face of the waveguide in response to the incident direction of the ray to the first end face of the waveguide, the reflected light from

the terminal mirror is diffused and radiated to the graded-index optical waveguide in all the directions within the predetermined angle range, and is propagated to all the positions on the first end face of the waveguide which is facing opposite to the flat plane of the bundling means. When the diffuser-reflector portion has a uniform diffusion power for the diffused and reflected light, light of uniform intensity is distributed to all the optical fibres.

According to a second aspect of the invention, there is provided an optical star coupler that includes: a bundling portion including a cylindrical tubular fibre bundle bundling a plurality of optical fibres each including a first end and a core, the first ends of the optical fibres being bundled and the first end faces of the optical fibres being formed to be a flat plane; a mixing portion including a cylindrical tubular waveguide including a first and a second end face, the first end face of the waveguide being coupled to the flat plane of the bundling portion and covering the cores of the optical fibres; and a first reflector portion coupled to the second end face of the waveguide.

When the cylindrical tubular waveguide is longer than the predetermined length, the signal light radiated to the waveguide from any one of the optical fibres diverges based on the numerical aperture (NA) of the optical fibre. However the diverging signal light is confined in the core of the waveguide, due to reflection in the periphery of the core of the waveguide. After multiple reflections, the light intensity distribution around the central axis (rotation of symmetry axis) of the cylindrical waveguide is minimised. That is, signal light is uniformly distributed over the radial cross-section of the core of the waveguide.

According to a third aspect of the invention, there is provided an optical star coupler that includes: a bundling portion including a polygonal fibre bundle bundling a plurality of optical fibres each including a first end and a core, wherein said first ends of said optical fibres are bundled and the end faces of the first ends of the optical fibres are arranged in a flat plane; a mixing portion including a polygonal waveguide rod including a first and a second end face, the first end face of the waveguide rod being coupled to the flat plane of the

bundling portion and covering the cores of the optical fibres; and a first reflector portion coupled to the second end face of the waveguide.

The waveguide of the mixing portion is formed as a polygonal-section rod which is longer than the predetermined length. The polygon may be triangular, rectangular or hexagonal, and a plurality of the polygons may cover a plane without leaving any gaps and without overlapping. The signal light radiated to the waveguide from any one of the optical fibres diverges based on the numerical aperture (NA) of the optical fibre. The diverging signal light is confined in the core of the waveguide, due to the reflection at the boundary of the core of the waveguide. After multiple reflections, the light intensity distribution across the core of the waveguide becomes uniform.

Advantageously, a second light reflector is formed on the flat plane of the bundling portion.

Preferably, the first reflector portion comprises a light diffuser-reflector.

Advantageously, the optical star coupler, further includes a reflector portion or a second reflector portion coupled to the flat plane of the bundling portion.

Preferably, the above described reflector portion or the second reflector portion is formed so as not to cover the end faces of the cores of the optical fibres.

Advantageously, the diffuser-reflector portion or the light diffuser-reflector includes a terminal mirror including a reflection plane and a transparent light diffusion layer formed between the second end face of the waveguide and the reflection plane of the terminal mirror.

Preferably, the light diffusion layer includes volume holograms.

The diffuser-reflector portion or the light diffuser-reflector may alternatively include a terminal mirror and minute uneven facets formed on the terminal mirror's face which is coupled to the mixing portion.

Preferably, the diffuser-reflector portion or the light diffuser-reflector includes minute uneven facets and a reflection plane which is formed on the second end face of the waveguide.

By these configurations, the optical signal light that had once failed to enter the optical fibres is reflected repeatedly by the light reflector of the bundling portion and the terminal mirror until it finally enters the optical fibres.

Embodiments of the invention will now be described in detail with reference to the accompanying drawings, in which:

Figure 1(A) is a schematic perspective view showing the structure of a first and second embodiment of an optical star coupler according to the present invention;

Figure 1(B) is a radial cross-section of the optical star coupler of Figure 1(A);

Figure 2(A) is a longitudinal cross-section showing a refractive index profile across the mixing means;

Figure 2(B) is a longitudinal cross-section showing another refractive index profile across the mixing means;

Figure 3(A) is a set of ray traces for explaining the propagation characteristics of an optical signal light through a first graded-index optical waveguide;

Figure 3(B) is a set of ray traces for explaining the propagation characteristics of an optical signal light through a second graded-index optical waveguide;

Figure 4 is a trace of incident and radiated light across a graded-index optical waveguide of the invention;

Figure 5(A) is a schematic perspective view showing the structure of a conventional optical star coupler;

Figure 5(B) is a radial cross-section of the conventional optical star coupler of Figure 5(A);

Figure 6(A) is a schematic perspective view showing the structure of another conventional optical star coupler;

Figure 6(B) is a longitudinal cross-section of the conventional optical star coupler of Figure 6(A);

Figure 7(A) is a schematic perspective view showing the structure of a third and fourth embodiment of an optical star coupler according to the present invention;

Figure 7(B) is a perspective view of the waveguide of the optical star coupler of Figure 7(A);

Figure 8(A) is a schematic perspective view showing the structure of a fifth embodiment of an optical star coupler according to the present invention;

Figure 8(B) is a perspective view of the waveguide of the optical star coupler of Figure 8(A);

Figure 9(A) is a cross-section of an optical waveguide whose cross-section is triangular;

Figure 9(B) is a cross-section of another optical waveguide whose cross-section is rectangular;

Figure 9(C) is a cross-section of still another optical waveguide whose cross-section is hexagonal;

Figures 10(A), 10(B) and 10(C) are light intensity distribution curves for explaining the change of optical power distribution in the optical star coupler of the third embodiment;

Figures 11(A), 11(B) and 11(C) are other light intensity distribution curves for explaining the change of optical power distribution in the optical star coupler of the fourth embodiment;

Figure 12 is a cross-section of a modified optical waveguide, the cross-section thereof is substantially rectangular;

Figure 13(A) is a schematic longitudinal cross-section of a conventional optical star coupler coupling seven optical fibres;

Figures 13(B) and 13(D) are schematic radial cross-sections showing the arrangement of the optical fibres of the optical star coupler of Figure 13(A);

Figure 13(C) is a light intensity distribution on the line A-B of Figure 13(B) when a light signal is radiated from the optical fibre 17 arranged in the central part of the waveguide 31; and

Figure 13(E) is a light intensity distribution on the line A-B of Figure 13(D) when a light signal is radiated from an optical fibre 11 arranged in the peripheral part of the waveguide.

Throughout the Figures, the parts corresponding to those of Figures 5(A), 5(B), 6(A), 6(B), 13(A), 13(B), 13(C), 13(D) and 13(E) are designated by like reference numerals.

The optical star coupler of the invention may be classified into three types.

A first type of the optical star coupler corresponds to the first and second embodiments. The mixing means of the optical star coupler comprises a circular-section cylindrical graded-index waveguide, and a light diffuser-reflector means at the end of the waveguide.

The second type of the optical star coupler corresponds to the third and fourth embodiments. The mixing means of the optical star coupler comprises a circular-section cylindrical tubular waveguide, and a light reflecting means or a diffuser-reflector means at the end of the waveguide.

A third type of the optical star coupler corresponds to the fifth embodiment. The mixing means of the optical star coupler comprises a polygonal-section waveguide rod, and a light reflecting means or a diffuser-reflector means on an end of the waveguide.

Referring now to Figures 1(A) and 1(B), an optical star coupler comprises a bundling means (or bundling portion) 2 for bundling the ends of a plurality of optical fibres 11 to 1E so that the fibres terminate with the end faces of their cores lying in the plane of an end face 21; a mixing means (or mixing portion) 3 including a waveguide 31 having a first end face 32, which contacts the end face 21 of the bundling means 2, and is wide enough to cover at least the cores 11a to 1Ea of the optical fibres 11 to 1E, and a second end face 33; and a diffuser-reflector means (or diffuser-reflector portion) 4 arranged on the second end face 33 of the mixing means 3.

In this configuration shown in Figures 1(A) and 1(B), optical signals 6a, 6b, radiated for example from an optical fibre 12, are diffused and reflected by the diffuser-reflector means 4 arranged on the second end face 33 of the mixing means 3. The optical signal, which radiates from an optical fibre and propagates through the mixing means 3, has hitherto been unevenly distributed across the cross-sectional area

parallel to the end faces 32, 33 of the mixing means in devices of the prior art. However, the reflected optical signal diverges almost uniformly by the diffusive reflection at the diffuser-reflector means 4 according to the present invention. As a result, the intensity of the light, that propagates in the mixing means back to the bundling means 2, distributes almost uniformly. Furthermore, the variation in the light intensity for the respective optical fibres 11 to 1E may be minimised irrespective of the displacement between the optical fibres 11 to 1E and the mixing means 3.

Referring now to Figures 7(A) and 7(B), an optical star coupler comprises a bundling means (or bundling portion) 2A for bundling the ends of a plurality of optical fibres 11 to 18 so as to form a cylindrical tubular fibre bundle 1 having an annular end face 21 on which the end faces of the cores of the fibres lie in an annular array; a mixing means (or mixing portion) 8 including a waveguide 81 having a cylindrical tubular core 81a, a first end face 32 and a second end face 33; and a light reflecting means (or reflecting portion) 4A arranged on the second end face 33 of the mixing means 8. The first end face 32 contacts the end face 21 of the bundling means 2A, and is wide enough to cover at least the cores 11a to 18a of the optical fibres 11 to 18.

In this configuration shown in Figures 7(A) and 7(B), the length 'z' of the waveguide 81 is arranged to be longer than a predetermined length z0. The waveguide 81 includes a cylindrical tubular outer cladding 81b surrounding the core 81a, and a cylindrical inner cladding 81c surrounded by the core 81a. The core 81a, the claddings 81b and 81c are formed coaxially with each other and the refractive indices of the claddings 81b and 81c differ from that of the core 81a. An optical signal radiated from any one of the optical fibres 11 to 18 into the waveguide 81 diverges based on the numerical aperture NA of the fibre bundle 1. The diverging optical signal is reflected at the boundaries between the core 81a and the claddings 81b and 81c, and the intensity of the light returning back to the optical fibres 11 to 18 exhibits little dependence on the radial angle θ and the position on the central axis Z (seen in Figure 7(B)). That is, a light signal with a uniform light intensity distribution propagates through the waveguide 81.

Referring now to Figures 8(A) and 8(B), an optical star coupler comprises a bundling means (or bundling portion) 2B for bundling the ends of a plurality of optical fibres 11 to 18 so as to form a polygonal fibre bundle 1 having a polygonal end face 21; a mixing means (or mixing portion) 9 including a waveguide 92 having a polygonal core 92a, a polygonal cladding 92b, a first end face 32 and a second end face 33; and a light reflecting means (or reflecting portion) 4C arranged on the second end face 33 of the mixing means 9. Generally, the waveguide 92 is a polygonal-section prismatic rod. In Figures 8(A) and 8(B), the waveguide 92 is illustrated as a rectangular-section rod. The first end face 32 contacts the end face 21 of the bundling means 2A, and is so dimensioned as to cover at least the cores 11a to 18a of the optical fibres 11 to 18.

In this configuration shown in Figures 8(A) and 8(B), the length 'z' of the waveguide 92 is arranged to be longer than the predetermined length z0. The waveguide 92 may alternatively be formed to be a polygonal rod such as a triangular-, rectangular- or hexagonal-section rod. A plurality of the polygonal rods may be arranged in parallel to each other with no gaps left in-between. An optical signal radiated from any one of the optical fibres 11 to 18 into the waveguide 81 diverges based on the numerical aperture NA of the fibre bundle 1. The diverging optical signal is reflected at the boundary between the core 92a and the cladding 92b. The intensity of the light returning back to the optical fibres 11 to 18 exhibits little dependence on the position in the waveguide 81.

Referring now to Figure 2(A), which is a longitudinal cross-section, a refractive index profile across the mixing means 3 is shown to illustrate a first embodiment of the invention. The optical star coupler of the first embodiment has a 'step-index' optical waveguide 31 that exhibits a uniform refractive index across the core thereof, as shown in Figure 2(A). The refractive index n of the core 31a is higher than the refractive index of the cladding 31b (referred to in Figure 1(A)), the light signals 6a, 6b propagate with a low transmission loss between the end faces 32 and 33 due to total internal reflection at the boundary between the core 31a and the cladding 31b.

Referring now back to Figures 1(A) and 1(B), fourteen optical fibres 11 to 1E (optical fibres 16 to 1E are omitted for clarity from Figure 1(A)) are bundled in the bundling means 2. The mixing means 3 includes a waveguide 31 that may be a large diameter optical fibre having a core, the cross-section of which is wider than the cross-section of the end face 21 of the bundle of the optical fibres 11 to 1E. The first end face 32 of the waveguide 31 is arranged in contact with the end face 21 of the optical fibres 11 to 1E. In the illustrated embodiment, the diffuser-reflector means 4 includes a terminal mirror 41 having a flat reflection plane 42, and a light diffusion layer (either one of layers 43, 44, or 45, usually represented by 43 when it is not necessary to distinguish these three from one another) is formed on the surface of the terminal mirror 41. The reflection plane 42 is coupled through the light diffusion layer 43 to the second end face 33 of the waveguide 31. The light diffusion layer 43 has minute unevenness on its surface and is made of a transparent material.

In the bundling means 2, the optical fibres 11 to 1E are bundled and fixed with adhesive filling the spaces between the optical fibres. The ends of the bundled optical fibres are polished to form a flat plane 21 that contacts with the mixing means 3. A light reflector 22 (reflection plane 23) is formed on the flat plane 21 (the flat plane 21 is also referred to as 'end face 21'). The light reflector 22 covers the entire surface except the end faces of the cores 11a to 1Ea of the optical fibres 11 to 1E. In other words, the light reflector 22 covers an area 10, shown as a hatched area, including the end faces of the claddings 11b to 1Eb, extending between the cores 11a to 1Ea. (Only the reference numeral 12a designating the core of the optical fibre 12 is described in the Figure.) The light reflector 22 is preferably formed by covering the end face 21 of the bundling means 2 with a negative-type photoresist, exposing and developing the photoresist with the light beams radiated from the optical fibres to leave the photoresist only on the end faces of the cores 11a to 1Ea, depositing a metal reflection film on the end face 21 of the bundling means 2, and removing the photoresist deposited on the end faces of the cores 11a to 1Ea of the optical fibres 11 to 1E.

Optical signals 6a , 6b radiating from any one of the optical fibres, e.g. the optical fibre 12, propagate through the core 31a of the waveguide 31 to the diffuser-reflector means 4 while diverging. Then, the optical signals 6a, 6b are diffused in the diffuser-reflector means 4 by the light diffusion layer 43 and reflected by the reflection plane 42. The reflected optical signals 6a, 6b are diffused again by the light diffusion layer 43, and propagate to the end face 32. The intensity distribution of the light initially propagating in the core 31a of the waveguide 31 towards the diffuser-reflector means 4 is not uniform. However, the intensity of the light twice diffused by the diffuser-reflector means 4 is equalised over the cross-section of the core 31a, and uniform intensity distribution is obtained for the light incident at the end face 32 of the waveguide 31 after returning from the reflection plane 42. Therefore, the intensity of the light impinging on the cores 11a to 1Ea of the optical fibres 11 to 1E is uniform when the end faces of the cores 11a to 1Ea are located inside the end face of the core 31a of the waveguide 31. Since the optical signals with uniform intensity are input to the optical fibres 11 to 1E, the intensity deviation among the distributed optical signals is minimised. The light that impinges on the light reflector 22 is reflected at the reflection plane 23 and propagates again through the waveguide 31. Thus, the optical signals 6a, 6b, once input to the waveguide 31, are reflected a large number of times by the diffuser-reflector means 4 and the light reflector 22 until the optical signals 6a, 6b are ultimately inputted to the optical fibres 11 to 1E, and are never radiated outside. Therefore, the optical star coupler of the invention facilitates transmitting the optical signal efficiently with low transmission loss.

Instead of arranging the reflection plane 42 and the light diffusion layer 43 separately, the optical signal may be diffused and reflected by using, as the terminal mirror 41, a light diffusion layer 45 having an uneven reflection plane consisting of minute facets. Moreover, in place of disposing the light diffusion layer 43 on the terminal mirror 41, the diffuser-reflector means 4 may be formed on the second end face 33 of the mixing means as a light diffusion layer 45 having a reflection

plane with minute uneven facets. These alternatives exhibit the same effect as the above described transparent diffusion layer 43 that has minute unevenness on its surface.

The diffuser-reflector means 4 may include a light diffusion layer 44, consisting of volume holograms, disposed between the second end face 33 of the mixing means 3 and the flat reflection surface 42 of the terminal mirror 41. A volume hologram is obtained by exposing photoresistive material such as polymers to a coherent diffused light. Any hologram that exhibits the desired optical diffusion characteristics may be obtained by selecting the diffusion angle range of the exposure light, light intensity distribution, wavelength, and incident light angle to the photoresistive material.

In the second embodiment, the structure of the optical star coupler is the same as that of the first embodiment except for the refractive index profile of the waveguide 31 of the mixing means 3. The 'graded-index' waveguide 31 has a refractive index profile as shown in Figure 1(B). The refractive index is higher near the central axis of the waveguide 31 and lower in the peripheral region but even here it is higher than the refractive index of the cladding 31b.

Referring now back to Figures 1(A) and 1(B), fourteen optical fibres 11 to 1E are bundled in a bundling means 2. The mixing means 3 including the waveguide 31 exhibits a refractive index profile that is higher around the central axis thereof. The first end face 32 of the waveguide 31 is arranged in contact with the end face 21 of the optical fibres 11 to 1E. A terminal mirror 41 having a flat reflection plane 42 is coupled to the second end face 33 of the waveguide 31 through a light diffusion layer 43. A light reflector 22 (reflection plane 23) is formed on the end face 21 so as to cover the entire end face 21 except the end faces of the cores 11a to 1Ea of the optical fibres 11 to 1E.

The refractive index distributes in rotational symmetry around the central axis of the waveguide 31. The refractive index is higher in the vicinity of the central axis and lower in the periphery of the waveguide 31. When the refractive index distribution in the waveguide 31 is expressed by the following equation (1), the path length of a

meridional ray (the ray that propagates in a plane containing the central axis of the waveguide) is constant between the incident and exit end faces of the waveguide irrespective of its incident position and incident angle to the waveguide 31.

$$n(r) = n_o . \operatorname{sech}(a.r) \qquad (1)$$

Here, n_o is a refractive index on the central axis, n(r) a refractive index at a position spaced by a distance r from the central axis, and 'a' a distribution constant.

When the refractive index distribution in the waveguide 31 is expressed by the following equation (2), the path length of a spiral ray (the ray that propagates spirally around the central axis of the waveguide) is constant between the incident and exit end faces of the waveguide irrespective of its incident position and incident angle to the waveguide 31.

$$n(r) = n_o .[1 + (a.r)^2]^{-1/2} \qquad (2)$$

Equations (1) and (2) may be approximated by equation (3) when the higher order terms including the term $(a.r)^4$ in an expanded power series may be neglected.

$$n(r) = n_o .[1 - (a.r)^2/2] \qquad (3)$$

Therefore, when the refractive index distributes radially from the central axis of the waveguide 31 and the higher order terms including the term $(a.r)^4$ may be neglected, the path length is nearly constant for any ray that propagates between the incident and exit end faces of the waveguide irrespective of its incident position and incident angle to the waveguide 31.

The trace T shown in Figure 4 of a meridional ray that propagates in a waveguide having a refractive index profile expressed by equation (3) is expressed by equation (4) that relates the spacing z between an incident end face 32 and exit end face 33; i.e. the length of the waveguide 31, the position r1 of the ray at the incident end face 32, the incident angle $\alpha 1$ of the ray to the incident end face 32, the position r2 of the ray at the exit end face 33, and the radiation angle $\alpha 2$ of the ray to the exit end face 33.

$r2 = r1.\cos(a.z) + [\alpha 1/(n_o.a)].\ \sin(a.z),$

$\alpha 2 = -\ r1.n_o.a.\sin(a.z) + \alpha 1.\cos(a.z)$ (4)

Especially, when $z=\pi/(2a)$, the relation of the incident and radiated rays is expressed from equation (4) by equation (5).

$r2 = \alpha 1/(n_o.a),$

$\alpha 2 = -r1.n_o.a$ (5)

When equation (5) holds, a ray that passes a point r1 on the incident end face 32 of the waveguide 31 radiates at a certain radiation angle $\alpha 2$ from the exit end face 33 irrespective of the incident angle $\alpha 1$, and the exit position r2 varies depending on the incident angle $\alpha 1$.

The waveguide 31 used in the second embodiment has a refractive index profile expressed by equation (3), and has a length of $\pi/(2a)$. Therefore, the above described equation (5) holds for the incident and radiated light in the second embodiment.

The diffuser-reflector means 4 in the second embodiment includes a light diffusion layer 44 having many minute volume holograms, and a terminal mirror 41 having a reflection plane 42. The minute holograms are formed by periodically changing the refractive index of a transparent medium. The volume hologram intensely diffracts a ray having a specific wavelength and impinging at a specific incident angle on the hologram. This specific condition is called the Bragg condition expressed by equation (6).

$\kappa d = \kappa i + \beta$ (6)

Here, κi and κd are an incident wave vector and a diffracted wave vector, respectively, and the directions thereof coincide with the propagation direction of the incident ray to the hologram and the direction of the diffracted ray diffracted by the hologram. The magnitude of the wave vector is $2\pi/\lambda$ for a wavelength λ. And, β represents a grating vector, the direction of which coincides with the normal line to the iso-refractive index surface of the hologram, and the magnitude thereof is $2\pi/p$ for the length p of one cycle of refractive index change in the hologram. Therefore, a pair of an incident ray and a diffracted ray that satisfies the Bragg condition exists for each minute hologram. Since the medium of the holograms is transparent, the rays which do not satisfy the Bragg condition pass through the minute holograms.

An incident ray to the diffuser-reflector means 4 passes through the minute holograms and is diffracted by a minute hologram that satisfies the Bragg condition. The diffracted rays diffracted by many holograms are radiated from the light diffusion layer 44 as a diffused light in total. An incident ray that has impinged on the diffuser-reflector means at another incident angle is diffracted by other minute holograms located in the propagation direction of the incident ray.

In the diffusion layer 44, the minute holograms are oriented at the same ratio to all the directions within the predetermined incident angle range described later so that the diffraction may occur evenly for all the pairs of the incident and diffraction directions. Therefore, an incident ray, whose incident angle to the diffusion layer 44 is within the predetermined angle range, may be diffused uniformly to all the directions within the predetermined angle range. The predetermined angle corresponds to the incident angle for the ray radiated from the outermost optical fibre, for that incident angle the incident ray may reach the light diffusion layer 44.

The optical star coupler of the second embodiment works in the following manner. Referring now to Figures 3(A) and 3(B), the optical signals 6a to 6g, which radiate from any one of the optical fibres (not shown), e.g. an optical fibre 12, propagate while refracted, and reach the light diffusion layer 44 that is in contact with the end face 33. Since the relation (5) holds in the 'graded-index' waveguide 31 of the second embodiment, the radiated ray directions from the end face 33, i.e. the direction of the incident ray relative to the light diffusion layer 44, is the predetermined angle $\alpha 2$ corresponding to the distance r1 between the core 12a of the optical fibre 12 and the central axis of the waveguide 31. Since Figure 3(A) shows only the traces 6a to 6g of the ray radiated from a point on the end of the core 12a at the angles determined by the numerical aperture (NA) of the optical fibre 12, the radiation angle of the ray from the end face 33 is the constant $\alpha 2$. The ray incident on the light diffusion layer 44 is diffused uniformly in all directions within the predetermined angle range. The predetermined angle is set at the incident angle for the ray radiated from the outermost optical fibre, so

that the incident rays from all the optical fibres may reach the light diffusion layer 44 and be within that selected angle.

The diffused rays from the light diffusion layer 44 are reflected by the reflection plane (not shown in Figures 3(A) and 3(B)), diffused again by the light diffusion layer 44, and impinge upon the illustrated continuous area a to g of the end face 33 of the waveguide 31. The incident direction (re-entrant direction) is distributed uniformly within the above described angle range defined by the light diffusion layer 44. Equation (5) holds also for the re-entrant rays, and the maximum re-entrant angle to the end face 33 corresponds to the position of the outermost optical fibre. Therefore, the optical signals 7a to 7g, which have propagated through the waveguide 33, focus at a point G, corresponding to the same re-entrant angle to the end face 33, on the end face 32. In total, the light reflected back distributes uniformly on the end face 32 within a circle, the radius of which corresponds to the distance between the central axis of the waveguide 31 and the outermost optical fibre. Thus, the intensity of light that reaches each of the cores 11a to 1Ea of the optical fibres is equalised. Since the light which has reached the cores 11a to 1Ea propagates through the optical fibres 11 to 1E, no deviation is caused in the distribution ratio for the incident optical signals and for the distributed optical signals.

The light that has impinged on the light reflector 22, i.e. the light that has failed to return to the cores of the optical fibres, is reflected by the reflection plane 23 and propagates again through the waveguide 31. Thus, the optical signals, once input to the waveguide 31, may be reflected many times by the diffuser-reflector means 4 and the light reflector 22 until the optical signals are input to the optical fibres 11 to 1E, and are never radiated outside. Therefore the optical star coupler of the invention facilitates transmitting the optical signal efficiently with low loss.

In the bundling means 2 of the second embodiment, the optical fibres 11 to 1E are bundled and fixed with an adhesive filling in the spaces between the optical fibres. The light reflector 22 may be formed in the same way as described above.

The 'graded-index' waveguide 31 is fabricated by the steps of forming a circular optical glass rod doped with monovalent ions, which exhibit large electronic polarisability and migrate easily in the glass at high temperature, and immersing the glass rod in a molten salt to exchange the doped ions and alkaline ions contained in the molten salt and to obtain the desired refractive index distribution based on the quasi-parabolic distribution of the diffused alkaline ions across the section of the rod.

An aggregate of the minute holograms that constitute the light diffusion layer 44 is obtained by irradiating a coherent diffused light onto a photosensitive material, e.g. a polymer whose refractive index changes with the exposure light intensity. Since the light intensity distribution on the interference fringes, formed by two light bundles which cross each other in the exposed photosensitive material, is stored as a hologram, the incident and diffracted light pair that satisfies the Bragg condition coincides with the light bundle pair irradiated on the photosensitive material. Therefore, by equalising the intensity distribution of the diffused light irradiated on the photosensitive material within the predetermined angle range required to the light diffusion layer 44, the intensity of any interference fringes formed by two crossing light bundles may be modulated at the same magnitude for any combinations of two directions within the predetermined angle range. Thus, the light diffusion layer 44 that exhibits the above described function is obtained.

In the embodiments described above, the length of the graded-index optical waveguide is set at $\pi/(2a)$. When the length z of the waveguide, having the same refractive index distribution, is expressed by the following equation (7), the incident ray direction from the second end face of the waveguide may be changed in response to the incident position of the ray at the first end face of the waveguide.

$$z = (2N + 1).\pi/(2a), \qquad (7)$$

where N is a positive integer.

In the embodiments described above, a hologram that transmits and diffuses the incident light is used for the light diffusion layer 44. Alternatively, a hologram that reflects and diffuses the incident light may be used for the light diffusion layer 44.

Referring now to Figures 7(A) and 7(B), a bundling means (or bundling portion) 2A bundles eight optical fibres 11 to 18 to form a cylindrical tubular fibre bundle. The end face of the fibre bundle forms a part of an end face 21 of the bundling means 2A. A mixing means (or mixing portion) 8 comprises a waveguide 81 which includes a cylindrical tubular core 81a, a cylindrical tubular cladding 81b and a solid cylindrical cladding 81c. The core 81a is so dimensioned as to cover the end faces of the cores 11a to 18a of the optical fibres 11 to 18. The claddings 81b and 81c cover the core 81a on its outer and inner longitudinal side faces. The cores 81a and claddings 81b, 81c are arranged such that the light which propagates through the core 81a satisfies the condition of total reflection and never leaks to the claddings 81b, 81c. On a first end face 32 of the waveguide 81, the end face of the core 81a contacts the end face 21 of the bundling means 2A such that the end face of the core 81a covers all the end faces of the cores 11a to 18a of the optical fibres 11 to 18. A reflection plane 23 is formed on the entire area of the end face 21 of the bundling means 2A except for the end faces of the cores 11a to 18a of the optical fibres 11 to 18. On an entire area of the second end face 33 of the waveguide 81, a terminal mirror 41 is disposed as a first reflector means or a first reflector portion 4A.

A cylindrical coordinate system (R Θ Z) will now be used for explaining the propagation of the incident light signal to the waveguide 81 from an optical fibre, e.g. the optical fibre 11. The origin of the cylindrical coordinate system is positioned at the centre of the end face 21 and its axis follows the cylinder axis of the waveguide 81. As shown in Figure 7(B), the radial length of the cylindrical waveguide 81 is represented by r, and the length of the waveguide 81 along the z-axis by z0. The z-axis is made to coincide with the central axis of the waveguide 81. The end face 21 of the bundling means 2A is in the plane of $z = 0$.

The cylindrical coordinate expresses the waveguide 81 by R, θ and z, where R=r, $-\pi \leq \theta \leq \pi$, and $0 \leq z \leq z0$.

Now, the position of the centre of the optical fibre is expressed by $(R, \Theta, Z) = (r,0,0)$. When a light signal is radiated from the optical fibre 11 in the positive direction of the z-axis, the dependence of the light intensity on the angle θ near the location of z=0 is represented approximately by the far field pattern of the optical fibre as shown in Figure 10(A). This narrow and sharp light intensity distribution is widened and flattened as shown in Figure 10(B) as the light propagates along the z-axis until the light intensity exhibits a flat distribution with little dependence on the angle θ as shown in Figure 10(B).

In the cylindrical coordinate system, the following relation holds.

$$\Theta = \theta + 2m\pi \qquad (8)$$

Here, $-\pi \leq \theta \leq \pi$, m represents all the integers, and Θ represents positions which are physically the same. Therefore, the light intensity at $\Theta = \theta$ is obtained by summing up the light intensities at $\theta + 2m\pi$ for all values of m in the range of $-\infty < m < \infty$. This is applicable after the signal light is reflected at the position Z=z0 by the terminal mirror 41.

By setting z0 at a value larger than the predetermined value, the dependence of the light intensity on the angle θ (gradient of the light intensity at the angle θ) becomes relatively smaller for the signal light which has returned back to the position of z=0 after being reflected by the terminal mirror 41. As shown by the solid curve in Figure 10(C), the gradient of the signal light intensity at the angle θ becomes smaller in the angle range ($-\pi \leq \theta \leq \pi$). At the same time, the light intensities outside the foregoing angle range (i.e. $\Theta \leq -\pi$, $\pi \leq \Theta$) are summed up after being translated by $2m\pi$ as indicated by the dotted lines in Figure 10(C). Therefore, the total light intensity P_{ALL} integrated in the range of $-\pi \leq \theta \leq \pi$ is made uniform. As a result, the intensities of the light signals inputted to the optical fibres 11 to 18 are equalised.

The centre of the optical fibre from which an optical signal radiates has been represented by $(R, \Theta, Z) = (r, 0, 0)$ so far. However, if one considers the symmetry of the angle Θ, the above explanation will hold for the position of the centre of an optical fibre represented generally by $(R, \Theta, Z) = (r, \theta, 0)$, where

$-\pi \leq \theta \leq \pi$

In the third embodiment, the flat end face 21 of the bundling means 2A is provided with a light reflector (or second reflector portion) 22. Specifically, the light reflector 22 comprises a reflection plane 23 formed on the entire area, excluding the end faces of the cores 11a to 18a of the optical fibres 11 to 18, where the core 81a of the waveguide 81 contacts. By this configuration, the optical signals which have been returned to the cores 11a to 18a are outputted, as they have been, through the optical fibres 11 to 18. Thus, an input optical signal is divided into output optical signals with little divide ratio distributions. The optical signals which have returned to the area outside the end faces of the cores 11a to 18a are reflected by the reflection plane 23 of the reflector 22, and propagate again through the core 81a of the waveguide 81. Thus, the optical signals, once put into the waveguide 81, may be reflected many times by the first reflector means 4A and the light reflector 22 until the optical signals are input to the optical fibres 11 to 1E, and are never radiated outside. Therefore the optical star coupler of the invention facilitates transmitting the optical signal efficiently with low loss.

Referring now to Figures 8(A) and 8(B), a bundling means (or bundling portion) 2B bundles eight optical fibres 11 to 18 such that a rectangular fibre bundle is formed and such that the end face of the fibre bundle forms a part of an end face 21 of the bundling means 2B. A mixing means (or mixing portion) 9 comprises a waveguide 92 which includes a rectangular core 92a covered by a cladding 92b. The cladding 92b covers the side faces of the core 92a, leaving a first and second end face 32 and 33 of the waveguide 92 unclad. The cores 92a and cladding 92b are arranged such that the light propagating through the core 92a satisfies the condition of total reflection and never leaks to the cladding 92b. On

the first end face 32 of the waveguide 92, the end face of the core 92a contacts the end face 21 of the bundling means 2B such that the end face of the core 92a covers all the end faces of the cores 11a to 18a of the optical fibres 11 to 18. A reflection plane 23 is formed on the entire area of the end face 21 of the bundling means 2B except for the end faces of the cores 11a to 18a of the optical fibres 11 to 18. Over the entire area of the second end face 33 of the waveguide 92, a terminal mirror 41 is disposed as a first reflector means (or first reflector portion) 4C.

An orthogonal coordinate system (X Y Z) will now be used for explaining the propagation of the incident light signal into the waveguide 92 from an optical fibre, e.g. the optical fibre 11. The origin of the orthogonal coordinate is positioned at the centre of the end face 21. As shown in Figure 8(B), the width of the rectangular waveguide 92 in the X-axis direction is represented by a, the height of the waveguide 92 in the Y-axis direction by b and the length of the waveguide 92 in the z-axis direction by z0. The Z-axis is made to coincide with the central axis of the waveguide 81. The end face 21 of the bundling means 2B is positioned in the plane Z=0. The orthogonal coordinate system expresses the waveguide 92 by X, Y and Z, where $-a/2 \leq X \leq a/2$, $-b/2 \leq Y \leq b/2$, and $0 \leq Z \leq z0$.

Though different from the illustrated example in Figures 8(A) and 8(B), the central position of the optical fibre is expressed by (X,Y,Z) =(0,0,0) and the core 92a is assumed to be very bulky for simplifying the following explanation. When a light signal is radiated from the optical fibre 11 in the positive direction of the Z-axis, the variation of the light intensity in the X-axis direction near the location of Z=0 is represented approximately by the far field pattern of the optical fibre as shown in Figure 11(A). This narrow and sharp light intensity distribution is widened and flattened as shown in Figure 11(B) as the light propagates along the Z-axis direction until the light intensity exhibits a flat distribution with little dependence on the coordinate in the X-axis direction as shown in Figure 11(C).

In the actual waveguide 92, the boundary between the core 92a and the cladding 92b crosses the X-axis at X= -a/2 and X=a/2, where the signal light is totally reflected. Since the rectangular waveguide 92 has two

pairs of total reflection planes; one of the pairs is parallel to the X=0 plane and the other one is parallel to the Y=0 plane. For example, the position of the boundary (total reflection plane) perpendicular to the X=0 plane is expressed by equation (9).

$$X = (2m-1).(a/2), \qquad (9)$$

where, m is any integer.

Therefore, the light intensity in the waveguide 92 is obtained by folding up the light intensity curve (the solid curve in Figures 11(A), 11(B) and 11(C)) at the positions expressed by equation (9), and by superimposing all the light intensities. This is applicable after the signal light is reflected at the position Z=z0 by the terminal mirror 41.

By setting z0 at a value larger than the predetermined value, the variation of the light intensity in the X direction becomes relatively smaller for the signal light which has returned back to the position Z=0 after being reflected by the terminal mirror 41. That is, the total light intensity P_{ALL} integrated in the range of $-a/2 \leq X \leq a/2$ is made uniform. As a result, the intensities of the light signals inputted to the optical fibres 11 to 18 are equalised in the X-direction.

The above explanation for the light intensity distribution in the X-axis direction is also applicable to explaining the light intensity distribution in the Y-axis direction. Therefore, by setting z0 at a value larger than the predetermined value, the total light intensity P_{ALL} integrated in the range of $-b/2 \leq Y \leq b/2$ is made uniform. As a result, the intensities of the light signals inputted to the optical fibres 11 to 18 are equalised in the Y-direction.

The centre of the optical fibre from which an optical signal radiates has been represented by (X, Y) =(0,0) so far. However, if one sets the centre of the optical fibre at an arbitrary position (X, Y) in the range of $-a/2 \leq X \leq a/2$ and $-b/2 \leq Y \leq b/2$, the foregoing explanation for the optical fibre centre of (X, Y) =(0,0) will hold, provided that the length z0 of the waveguide is long enough to flatten the integrated intensity P_{ALL} of the signal light.

As explained above, the intensity distribution of the light signals inputted to the optical fibres 11 to 18 is minimised by arranging the length of the rectangular waveguide rod 92 to be longer than the predetermined value.

Figures 9(A), 9(B) and 9(C) show schematic cross-sections of various polygonal-section optical waveguides. Figure 9(A) shows a core 91a of a waveguide 91 which is triangular in section. Figure 9(B) shows a rectangular-section core 92a, and Figure 9(C) shows a core 93a which is hexagonal in section.

In the illustrated polygonal-section waveguides, the integrated signal light intensity P_{ALL} is obtained, due to the total reflection at the boundaries between the core 91a, 92a or 93a and the cladding 91b, 92b or 93b, by folding up the light intensities along the dotted lines and by superimposing all the folded light intensities in the polygon surrounded by the solid lines. Since the illustrated polygons can cover a plane without leaving any gaps and without overlapping, the signal light inputted to an arbitrary location inside any one of the illustrated polygons is outputted to the optical fibres with little intensity distribution by setting the length of the polygonal waveguide rods to be longer than the predetermined value.

The edge corners of the polygons may be cut out or rounded. The cut out or rounded edge corners cause gaps which may further cause intensity variation of the signal light outputted to the optical fibres. However, the signal light intensity distribution may be harmless in practice if the cut out or rounded portions are sufficiently small.

In the third and fourth embodiments shown in Figure 7(A), the first reflector portion (or first reflector means) 4A or 4C disposed on the second end face 33 of the waveguide 81, 91, 92 or 93 may be replaced by a light diffuser-reflector (or diffuser-reflector means) 4B or 4D. As described earlier in conjunction with the first and second embodiments (Figure 1(A)), the light diffuser-reflector 4B or 4D may be formed by disposing a transparent light diffusion layer 43, which has many minute concave and convex surface portions, between the second end face 33 of the mixing means 8 or 9 and the flat reflection plane 42 of the terminal mirror 41.

Alternatively, instead of forming the reflection plane 42 and the light diffusion layer 43 separately, the diffuser-reflector means 4B or 4D may consists of a light diffusion layer 45 having, on the surface thereof, many concave and convex reflection portions for diffusing and reflecting the signal light.

Still alternatively, instead of forming the diffuser-reflector means 4B or 4D on the side of the terminal mirror 41, the diffuser-reflector means 4B or 4D, consisting of a light diffusion layer 45 having many concave and convex portions on one surface and a reflection plane on another surface thereof, may be formed on the second end face 33 of the mixing means 8 or 9. In the above described alternatives, the light diffusion layer 45 exhibits the same function with that of the transparent light diffusion layer 43 having many minute concave and convex surface portions.

As a further alternative, the light diffuser-reflector 4B or 4D may be formed by disposing a light diffusion layer 44, including minute volume holograms, between the second end face 33 of the mixing means 8 or 9 and the flat reflection plane 42 of the terminal mirror 41. These volume holograms are obtained by the same methods as have been described above.

The light diffuser-reflector 4B or 4D facilitates shortening the length z0 of the cylindrical waveguide 81 of the mixing means 8, or polygonal waveguides 91, 92, 93 of the mixing means 9. The light diffuser-reflector 4B or 4D also facilitates equalising the intensities of the signal light divided to the optical fibres.

As has been explained above, the present invention equalises the intensity distribution of the optical signal light that propagates through the mixing means by forming a light diffusion layer on the reflection plane of the terminal mirror. As a result, the distribution ratios of the light radiated from an optical fibre and the incident light to the optical fibres do not exhibit a large deviation from one another even when the optical fibres are displaced to some extent from the mixing means.

Since the incident optical signal light from any one of the optical fibres to the waveguide is diffused in the light diffusion layer and the diffused light propagates back to the incident end face of the waveguide, the light intensity distribution on the incident end face of the waveguide is equalised and made uniform. Therefore, the distribution ratios of the light radiated from an optical fibre and the incident light to the other optical fibres exhibit a minimum deviation from one another even when the optical fibres are displaced to some extent from the mixing means.

By the provision of the light reflector on the contact faces of the mixing means and the bundling means except on the end faces of the cores of the optical fibres, the optical signals input to the mixing means are reflected many times until the optical signals are coupled to the optical fibres and are never radiated outside. Thus, the optical signals are efficiently transmitted with low transmission loss.

By shaping the waveguide of the mixing means as a circular-section cylindrical or polygonal-section rod which is longer than the predetermined length, the intensity variation of the output signal light to the respective optical fibres is minimised.

As a result, an optical star coupler is obtained which improves the spacing factors of the optical fibres and mixing means, and which distributes the optical signal radiated from an optical fibre uniformly across the mixing means and couples the distributed optical signal efficiently to the other optical fibres.

CLAIMS

1. An optical star coupler comprising:

a bundling portion comprising a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the end faces of the first ends of the optical fibres are arranged to be in a flat plane;

a mixing portion comprising a waveguide including a first and a second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and

a diffuser-reflector portion coupled to the second end face of the waveguide.

2. An optical star coupler according to claim 1, wherein the waveguide is formed from a transmission medium whose refractive index is graduated from a higher refractive index at the waveguide's central axis to a lower refractive index at the waveguide's periphery.

3. An optical star coupler according to claim 2, wherein the first and second end faces of the waveguide are spaced at a selected distance which fixes an exit portion of a ray on the second end face in response to the ray's incident direction applied at the first end face of the waveguide.

4. An optical star coupler comprising:

a bundling portion comprising a cylindrical tubular fibre bundle bundling a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the end faces of the first ends of the optical fibres are arranged to be in a flat plane;

a mixing portion comprising a cylindrical tubular waveguide including a first and a second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and

a first reflector portion coupled to the second end face of the waveguide.

5. An optical star coupler comprising:

a bundling portion comprising a polygonal fibre bundle bundling a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the faces of the first ends of the optical fibres are arranged to be a flat plane;

a mixing portion comprising a polygonal waveguide including a first and second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and

a first reflector portion coupled to the second end face of the waveguide.

6. An optical star coupler according to claim 4 or claim 5, wherein the first reflector portion comprises a light diffuser-reflector.

7. An optical star coupler according to claim 1, claim 4 or claim 5, further comprising a second reflector portion coupled to the flat plane of the bundling portion.

8. An optical star coupler according to claim 7, wherein the reflector portion is not formed on the end faces of the cores of the optical fibres.

9. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises a terminal mirror including a reflection plane and a transparent light diffusion layer formed between the second end face of the waveguide and the reflection plane of the terminal mirror.

10. An optical star coupler according to claim 9, wherein the light diffusion layer comprises volume holograms.

11. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises a terminal mirror and minute uneven facets formed on the terminal mirror's face which is coupled to the mixing portion.

12. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises minute uneven facets and a reflection plane which is formed on the second end face of the waveguide.

13. An optical star coupler substantially as herein described with reference to Figures 1 to 4, Figures 7, Figures 8, or Figures 9 to 12 of the accompanying drawings.

Amendments to the claims have been filed as follows

CLAIMS

1. An optical star coupler comprising:
a bundling portion comprising a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the end faces of the first ends of the optical fibres are arranged to be in a flat plane;
a mixing portion comprising a waveguide including a first and a second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and
a diffuser-reflector portion coupled to the second end face of the waveguide.

2. An optical star coupler according to claim 1, wherein the waveguide is formed from a transmission medium whose refractive index varies from a higher refractive index at the waveguide's central axis to a lower refractive index at the waveguide's periphery.

3. An optical star coupler according to claim 2, wherein the first and second end faces of the waveguide are spaced at a selected distance which fixes an exit portion of a ray on the second end face in response to the ray's incident direction applied at the first end face of the waveguide.

4. An optical star coupler comprising:
a bundling portion comprising a cylindrical tubular fibre bundle bundling a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the end faces of the first ends of the optical fibres are arranged to be in a flat plane;
a mixing portion comprising a cylindrical tubular waveguide including a first and a second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and
a first reflector portion coupled to the second end face of the waveguide.

5. An optical star coupler comprising:

a bundling portion comprising a polygonal fibre bundle bundling a plurality of optical fibres each including a first end and a core, wherein the first ends of the optical fibres are bundled and the faces of the first ends of the optical fibres are arranged to be a flat plane;

a mixing portion comprising a polygonal waveguide including a first and second end face, wherein the first end face of the waveguide is coupled to the flat plane of the bundling portion and covers the cores of the optical fibres; and

a first reflector portion coupled to the second end face of the waveguide.

6. An optical star coupler according to claim 4 or claim 5, wherein the first reflector portion comprises a light diffuser-reflector.

7. An optical star coupler according to claim 1, claim 4 or claim 5, further comprising a second reflector portion coupled to the flat plane of the bundling portion.

8. An optical star coupler according to claim 7, wherein the reflector portion covers the entire surface except the end faces of the cores of the optical fibres.

9. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises a terminal mirror including a reflection plane and a transparent light diffusion layer formed between the second end face of the waveguide and the reflection plane of the terminal mirror.

10. An optical star coupler according to claim 9, wherein the light diffusion layer comprises volume holograms.

11. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises a terminal mirror and minute uneven facets formed on the terminal mirror's face which is coupled to the mixing portion.

12. An optical star coupler according to claim 1 or claim 6, wherein the diffuser-reflector portion comprises minute uneven facets and a reflection plane which is formed on the second end face of the waveguide.

13. An optical star coupler substantially as herein described with reference to Figures 1 to 4, Figures 7, Figures 8, or Figures 9 to 12 of the accompanying drawings.

The Patent Office

36

Application No: GB 9622270.8
Claims searched: 1 and appendant claims
Examiner: Richard Nicholls
Date of search: 9 January 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G2J (JGEC) ; H4B (BK20S1)

Int Cl (Ed.6): G02B ; H04B 10/20

Other: Online : WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	NONE	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		